The National Ignition Facility and Basic Science

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May 6, 2006

Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.
National Ignition Facility

Stockpile Stewardship  Basic Science  Fusion Energy

Peer-reviewed Basic Science is a fundamental part of NIF’s go-forward plan
Our vision: open NIF to the outside scientific community to pursue frontier HED laboratory science

[http://www.nas.edu/bpa/reports/cpu/index.html]
NIF concentrates all the energy in a football stadium-sized facility into a mm\(^3\).

- **Matter Temperature**: \(>10^8 \text{ K}\)
- **Radiation Temperature**: \(>3.5 \times 10^6 \text{ K}\)
- **Densities**: \(>10^3 \text{ g/cm}^3\)
- **Pressures**: \(>10^{11} \text{ atm}\)
NIF’s Unprecedented Scientific Environments:

• $T > 10^8$ K matter temperature
• $\rho > 10^3$ g/cc density

Those are both 7x what the Sun does! Helium burning, stage 2 in stellar evolution, occurs at $2 \times 10^8$ K!

• $\rho_n = 10^{26}$ neutrons/cc

Core-collapse Supernovae, colliding neutron stars, operate at $\sim 10^{21}$!

• Electron Degenerate conditions
  Rayleigh-Taylor instabilities for (continued) laboratory study.

These apply to Type Ia Supernovae!

• Pressure $> 10^{11}$ bar
  Only need $\sim$Mbar in shocked hydrogen to study the EOS in Jupiter & Saturn

These certainly qualify as “unprecedented.” And Extreme!
NIF flux (cm$^{-2}$s$^{-1}$) vs other neutron sources

Neutrons/cm$^2$•s

- LANSCE/WNR: $10^{8.9}$
- Reactor: $10^{13.15}$
- SNS: $10^{14.16}$
- NIF: $10^{33.36}$

Supernovae
The NRC committee on HEDP issued the “X-Games” report detailing this new science frontier:

Findings:
- HEDP offers frontier research opportunities in:
  - Plasma physics
  - Laser and particle beam physics
  - Condensed matter and materials science
  - Nuclear physics
  - Atomic and molecular physics
  - Fluid dynamics
  - Magnetohydrodynamics
  - Astrophysics

NIF is the premier facility for exploring extreme conditions of HEDP.
The NRC committee on the Physics of the Universe highlighted the new frontier of HED Science

Eleven science questions for the new century:

2. What is the nature of dark energy?
   — Type 1A SNe (burn, hydro, rad flow, EOS, opacity)

4. Did Einstein have the last word on gravity?
   — Accreting black holes (photoionized plasmas, spectroscopy)

6. How do cosmic accelerators work and what are they accelerating?
   — Cosmic rays (strong field physics, nonlinear plasma waves)

8. Are there new states of matter at exceedingly high density and temperature?
   — Neutron star interior (photoionized plasmas, spectroscopy, EOS)

10. How were the elements from iron to uranium made and ejected?
    — Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow, r-process)

• HEDP provides crucial experiments to interpret astrophysical observations
Core-collapse supernova explosion mechanisms remain uncertain

- SN observations suggest rapid core penetration to the “surface”
- This observed turbulent core inversion is not yet fully understood

**Standard (spherical shock) model**

- Pre-supernova structure is multilayered
- Supernova explodes by a strong shock
- Turbulent hydrodynamic mixing results
- Core ejection depends on this turbulent hydro.
- Accurate 3D modeling is required, but difficult
- Scaled 3D testbed experiments are possible

![Standard (spherical shock) model diagram](image)

**Jet model**

![Jet model diagram](image)

[Kifonidis et al., AA. 408, 621 (2003)]
Three university teams are starting to prepare for NIF shots in unique regimes of HED physics

<table>
<thead>
<tr>
<th>Astrophysics - hydrodynamics</th>
<th>Planetary physics - EOS</th>
<th>Nonlinear optical physics - LPI</th>
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<tbody>
<tr>
<td>Paul Drake, PI, U. of Mich.</td>
<td>Raymond Jeanloz, PI, UC Berkeley</td>
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<tr>
<td>David Arnett, U. of Arizona</td>
<td>Thomas Duffy, Princeton U.</td>
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<tr>
<td>Tomek Plewa, U. of Chicago</td>
<td>Yogendra Gupta, Wash. State U.</td>
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<tr>
<td>Todd Ditmire, U. Texas-Austin</td>
<td>Paul Loubeyre, U. Pierre &amp; Marie Curie, and CEA</td>
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<tr>
<td>LLNL hydrodynamics team</td>
<td>LLNL EOS team</td>
<td>Christoph Niemann, PI,</td>
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<td></td>
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<td>UCLA NIF Professor</td>
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<td></td>
<td></td>
<td>Chan Joshi, UCLA</td>
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<td></td>
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<td>Warren Mori, UCLA</td>
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<td></td>
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<td>Bedros Afeyan, Polymath</td>
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<td></td>
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<td>David Montgomery, LANL</td>
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<td></td>
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<td>Andrew Schmitt, NRL</td>
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<tr>
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<td>LLNL LPI team</td>
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Comparison of $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$ measured at an accelerator lab and using NIF

**Accelerator-Based Experiments**

- **S-Factor (keV barn)**
  - $E$ (keV)
  - $S$-Factor

<table>
<thead>
<tr>
<th>$E$ (keV)</th>
<th>$S$-Factor</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>400</td>
<td>0.4</td>
</tr>
<tr>
<td>800</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**

- **Validation**
  - ✔️ Mono-energetic
  - ❌ Low event rate at low energies
  - ✕ Significant screening corrections needed
  - ✕ Not performed at relevant energies

**NIF-Based Experiments**

- **10$^{17}$ 3He atoms**
- **3He(4He,γ)7Be**
- **3He(4He,γ)7Be**

- **Validation**
  - ✔️ High Count rate (3x10$^5$ atoms/shot)
  - ✔️ Small, manageable screening
  - ✔️ Energy window is better (a bit high)
  - ✕ Integral experiment
  - ✕ 7Be background
Stellar Astrophysics at NIF: Measurements of Basic Thermonuclear Reactions

- Thermonuclear Reaction Rates between species i and j are of the form:

  \[ R \sim \langle \sigma_{ij} \nu \rangle_f \]

  \[ \sigma_{ij} = \frac{S_{ij}(\varepsilon_p)}{\varepsilon_p} e^{-\pi(\varepsilon_G/\varepsilon_p)^{1/2}} \]

- S factors are extrapolated to the relevant stellar Gamow ‘weighting’ regions from higher energy experimental data – laboratory ‘cold’ electron screening effects are significant

- Thermonuclear reactions can be observed in ‘passive’ NIF implosions or as by products of the temperature runaway in d + t burn -but measurements challenging!

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Estimated Number of Reactions</th>
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<tbody>
<tr>
<td>(^3\text{He}(^3\text{He},2\text{p})\alpha)</td>
<td>(~ 10^8) reactions at 8 keV in 20 ps (10(^{17}) initial nuclei, note ‘targets’)</td>
</tr>
<tr>
<td>(^7\text{Be}(\text{p},\gamma)^8\text{B})</td>
<td>(~ 4 \times 10^4) reactions</td>
</tr>
<tr>
<td>(^3\text{He}(\alpha,\gamma)^7\text{Be})</td>
<td>(~ 3 \times 10^5) reactions</td>
</tr>
<tr>
<td>(^{15}\text{N}(\text{p, }\alpha)^{12}\text{C})</td>
<td>(~ 6 \times 10^6) reactions</td>
</tr>
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A unique NIF opportunity: Study of Three-Body Reactions in the r-Process

- Currently believed to take place in supernovae, but we don’t know for sure

- r-process abundances depend on:
  — Weak decay rates far from stability
  — Nuclear masses far from stability

- The cross section for the $\alpha + \alpha + n \rightarrow ^9\text{Be}$ reaction
\( \alpha + \alpha + n \rightarrow ^9\text{Be} \) is the “Gatekeeper” for the r-Process

- If this reaction is strong, \(^9\text{Be}\) becomes abundant, \(\alpha + ^9\text{Be} \rightarrow ^{12}\text{C} + n\) is frequent, and the light nuclei will all have all been captured into the seeds by the time the r-process seeds get to \(~\text{Fe}\)

- If it’s weak, less \(^{12}\text{C}\) is made, and the seeds go up to mass 100 u or so; this seems to be what a successful r-process (at the neutron star site) requires

- The NIF target would be a mixture of \(^2\text{H}\) and \(^3\text{H}\), to make the neutrons, with some \(^4\text{He}\) (and more \(^4\text{He}\) will be made during ignition). *This type of experiment can’t be done with any other facility that has ever existed*
Eleven science questions for the new century:

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    — Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow)

• HEDP provides crucial experiments to interpreting astrophysical observations
• We envision that NIF will play a key role in these measurements
Core-collapse supernova explosion mechanisms remain uncertain

- A new model of Supernova explosions: from Adam Burrows et al.
- A cutaway view shows the inner regions of a star 25 times more massive than the sun during the last split second before exploding as a SN, as visualized in a computer simulation. Purple represents the star’s inner core; Green (Brown) represents high (low) heat content.
  
  - In the Burrows model, after about half a second, the collapsing inner core begins to vibrate in “g-mode” oscillations. These grow, and after about 700 ms, create sound waves with frequencies of 200 to 400 hertz. This acoustic power couples to the outer regions of the star with high efficiency, causing the SN to explode.

- Burrows’ solution hasn’t been accepted by everyone; it’s very different from any previously proposed.

From http://www.msnbc.msn.com/id/11463498/
Opacity experiments on iron led to an improved understanding of Cepheid Variable pulsation

- The measured opacities of Fe under relevant conditions were larger than originally calculated
- New OPAL simulations reproduced the data
- The new opacity simulations allowed Cepheid Variable pulsations to be correctly modeled
- “Micro input physics” affecting the “macro output dynamics”

[Rogers & Iglesias, Science 263,50 (1994);
Da Silva et al., PRL 69, 438 (1992)]